



Elliptic Anisotropy v_2 May Be Dominated by Particle Escape instead of Hydrodynamic Flow

Zi-Wei Lin,^a Liang He,^b Terrence Edmonds,^c Feng Liu,^d Denes Molnar,^b Fuqiang Wang^{b,d}

^a Department of Physics, East Carolina University, Greenville, NC 27858, USA

^b Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA

^c Department of Physics, University of Florida, Gainesville, FL 32611, USA

^d Key Laboratory of Quark & Lepton Physics (Central China Normal University), Ministry of Education, China

Abstract

It is commonly believed that azimuthal anisotropies in relativistic heavy ion collisions are generated by hydrodynamic evolution of the strongly interacting quark-gluon plasma. Here we use transport models to study how azimuthal anisotropies depend on the number of collisions that each parton suffers. We find that the majority of v_2 comes from the anisotropic escape of partons, not from the parton collective flow, for semi-central Au+Au collisions at 200A GeV. As expected, the fraction of v_2 from the anisotropic particle escape is even higher for smaller systems such as d+Au. Our transport model results also confirm that azimuthal anisotropies would be dominated by hydrodynamic flow at unrealistically-high parton cross sections. Our finding thus naturally explains the similarity of azimuthal anisotropies in small and large systems; however, it presents a challenge to the paradigm of anisotropic flow.

Keywords: quark-gluon plasma, anisotropic flow, transport model, hydrodynamics

1. Introduction

A main goal of relativistic heavy ion collisions is to create the quark-gluon plasma (QGP) and then study its properties in order to better understand quantum chromodynamics at extreme conditions. In non-central heavy ion collisions, the overlap volume of the colliding nuclei is anisotropic in the transverse plane even when event-by-event fluctuations in the initial geometry are neglected, and large final-state azimuthal anisotropies in the momentum space have been measured and described well by hydrodynamics [1]. Transport models such as A Multi-Phase Transport (AMPT) [2] can also describe the observed final-state anisotropic flow. It is thus commonly believed that azimuthal anisotropies (in large colliding systems at least) are generated by the hydrodynamic evolution of the strongly-interacting QGP and that the evolution of a large system in transport models is qualitatively the same as that in hydrodynamics.

Recently, anisotropy signals have been observed in small systems of p+Pb collisions at the LHC [3] and d+Au collisions at RHIC [4], and the signals can again be described by both hydrodynamics [5] and the

AMPT transport model [6]. A natural question is whether hydrodynamics is still applicable to such small systems. So we investigate the generation of azimuthal anisotropies in transport models by analyzing all parton collisions in semi-central Au+Au collisions and central d+Au collisions at $\sqrt{s} = 200A$ GeV [7]. We use the string melting version of the AMPT model [8, 2], and parton scatterings are treated with the ZPC elastic parton cascade [9]. We analyze the complete history of parton interactions in AMPT from the initial encounter of the colliding nuclei to the final-state partons. We also use another transport model, the MPC/Cascade [10], to check the model dependence of our results.

2. Results

We define N_{coll} as the number of collisions that a parton suffers with other partons. Fig.1 shows the normalized probability distributions of partons that freeze out after N_{coll} collisions for semi-central Au+Au collisions at the impact parameter $b = 7.3$ fm (solid curve) and central d+Au collisions at $b = 0$ fm (dashed curve). We see that about 14% of partons in the Au+Au collisions do not scatter at all before they freeze out, while this fraction is much higher at 48% for d+Au collisions. Summing over all possible N_{coll} values, we get the average number of collisions as $\langle N_{\text{coll}} \rangle = 4.6$ for Au+Au collisions ($b = 7.3$ fm) and 1.2 for d+Au collisions ($b = 0$ fm) respectively.

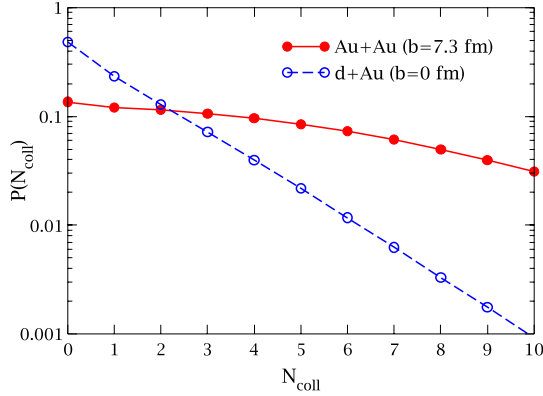


Fig. 1. (color online) Normalized probability distributions of partons that freeze out after N_{coll} collisions: solid and dashed curves are for Au+Au and d+Au collisions, respectively.

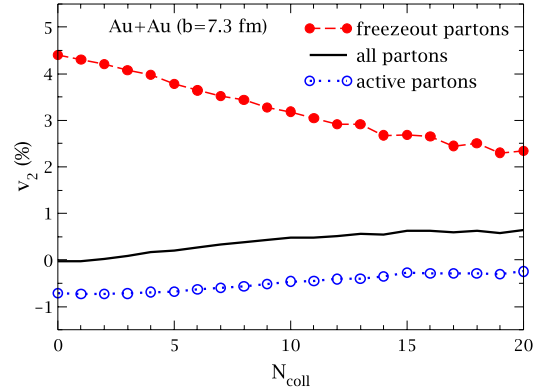


Fig. 2. Parton v_2 in Au+Au collisions versus N_{coll} : dashed curve for partons that freeze out after exactly N_{coll} collisions, dotted curve for partons continuing to interact after N_{coll} collisions, solid curve for the sum of these two parton populations.

Fig.2 shows the parton v_2 as a function of the number of collisions N_{coll} for different parton populations in Au+Au collisions. The dashed curve shows v_2 of partons that freeze out after exactly N_{coll} collisions, while the dotted curve is for partons that continue to scatter after N_{coll} collisions. The sum of these two parton populations is shown by the solid curve and labeled “all partons”; however, note that it represents all partons that have already scattered N_{coll} times, not all partons in the collisions (except when $N_{\text{coll}} = 0$). Fig.2 shows that freezeout partons at $N_{\text{coll}} = 0$ have a large positive v_2 ; this is fully due to the anisotropic escape probability since it is easier for a parton to escape (i.e. freeze out) along the shorter axis of the transverse overlap area. The solid curve at $N_{\text{coll}} = 0$ shows zero v_2 because the initial all-parton v_2 is zero due to the azimuthal symmetry in the transverse momentum distribution of initial partons. It is interesting to see that active partons at $N_{\text{coll}} = 0$, i.e., all partons that will scatter once or more times during the parton evolution, have an initial v_2 that is negative. However, this is only natural since at $N_{\text{coll}} = 0$ the v_2 of active partons must have the opposite sign as the v_2 of freezeout partons so that the total initial v_2 is zero. We also see that the same qualitative features at $N_{\text{coll}} = 0$ are repeated at higher N_{coll} values in Fig.2, i.e., partons that freeze out after a given N_{coll} collisions continue to have a significant positive v_2 , active partons at a given N_{coll} continue to have a negative v_2 , while the sum has a small or near-zero v_2 .

The final average elliptic flow of all partons $\langle v_2 \rangle$ includes partons that freeze out at different N_{coll} (0, 1, 2, ...), but freezeout partons at $N_{\text{coll}} \neq 0$ obtain a positive v_2 due to two effects: 1) the anisotropic es-

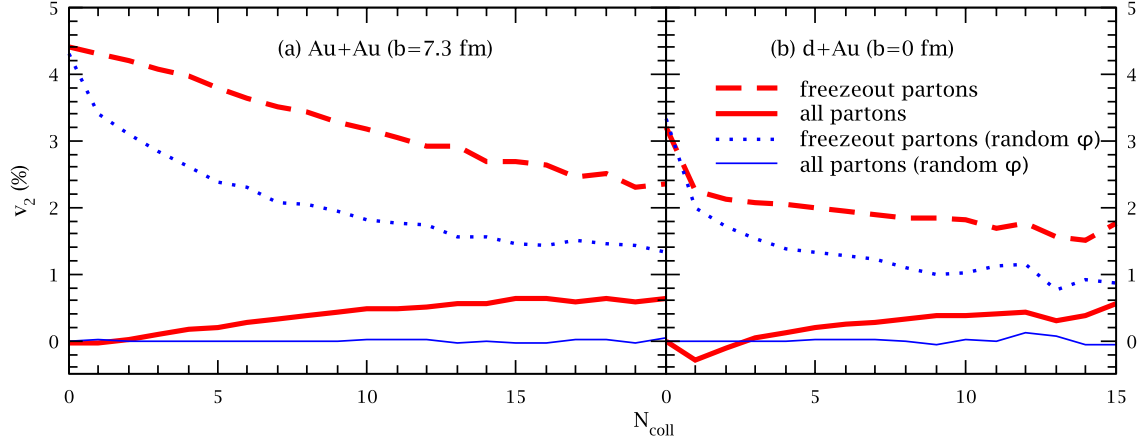


Fig. 3. Parton v_2 as a function of the number of collisions N_{coll} in (a) Au+Au and (b) d+Au collisions from both normal (thick curves) and azimuth-randomized (thin curves) AMPT results.

cape probability due to spatial anisotropy, and 2) their anisotropic collective flow (or the space-momentum correlation) that is generated by parton scatterings during the evolution. So a key question is which effect is more important. Note that both effects are due to parton scatterings and thus inseparable in the space-time evolution. In order to estimate the contribution from the escape mechanism, i.e., from the anisotropic escape probability if there were no space-time correlation in the partons during the evolution, we design the azimuth-randomized test [7]. In test simulations, we randomize the ϕ angle while keeping the same magnitude for the transverse momentum of each of the two final-state partons after each parton scattering.

As shown by the thin solid line in Fig.3(a) for Au+Au collisions and in Fig.3(b) for d+Au collisions, the “all partons” v_2 in the azimuth-randomized test is essentially zero at any given N_{coll} value. This confirms that we have destroyed the collective flow of partons that have suffered any given number of scatterings N_{coll} . Some of these partons will not scatter again and thus freeze out after exactly N_{coll} scatterings; they still have a significant positive v_2 , as shown by the dotted lines in Fig.3. Since the random test removes the azimuthal preference and space-momentum correlation due to the collective flow, the freezeout parton v_2 comes purely from the escape mechanism. Fig.3 also shows that the freezeout parton v_2 in the random test is lower than the normal AMPT results (dashed curves) at $N_{\text{coll}} \neq 0$; this is expected since the random test results lack the v_2 contribution from the collective flow. On the other hand, at $N_{\text{coll}} = 0$ the freezeout parton v_2 in the random test is essentially the same as the normal results; this is because it is determined only by the initial spatial anisotropy, which is not affected by the azimuth randomization.

Summing the freezeout parton v_2 over all possible N_{coll} values with freezeout probabilities (shown in Fig.1 for normal events and similar for the random tests) as the weight, we get the final average elliptic flow $\langle v_2 \rangle$ at 3.9% for normal events and 2.7% for azimuth-randomized events for the Au+Au collisions. Fig.3(b) shows AMPT results for central d+Au collisions, which are qualitatively the same as those for Au+Au collisions, while $\langle v_2 \rangle$ is 2.7% for normal events and 2.5% for azimuth-randomized events. Therefore a majority of v_2 comes from the escape mechanism for both collision systems. In addition, although the v_2 magnitudes for freezeout partons are lower in d+Au collisions as expected, they are not drastically lower despite a factor of ~ 4 lower $\langle N_{\text{coll}} \rangle$. This is because partons obtain their v_2 mainly through successive freezeout (at different N_{coll}) in response to the spatial anisotropy, not mainly from the hydrodynamic-type flow that gradually builds up after many scatterings.

The parton cross section used in the AMPT results shown above is $\sigma = 3$ mb, which is determined from comparisons with the bulk pion and kaon data on dN/dy , p_T spectra and $v_2(p_T)$ in heavy ion collisions at 200A GeV and 2760A GeV [11]. We have seen that the corresponding average number of collisions $\langle N_{\text{coll}} \rangle$ is modest (4.6) for semi-central Au+Au collisions and low (1.2) for central d+Au collisions. On the other hand, at high-enough $\langle N_{\text{coll}} \rangle$ we expect transport models to approach hydrodynamics, where we can also expect the final $\langle v_2 \rangle$ to be dominated by hydrodynamic-type flow instead of the escape mechanism.

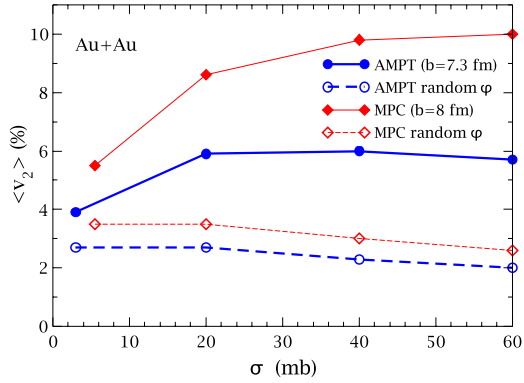


Fig. 4. Parton v_2 as a function of the parton cross section; 3 mb is the value at which the string melting AMPT model reasonably reproduces bulk data including pion and kaon $v_2(p_T)$.

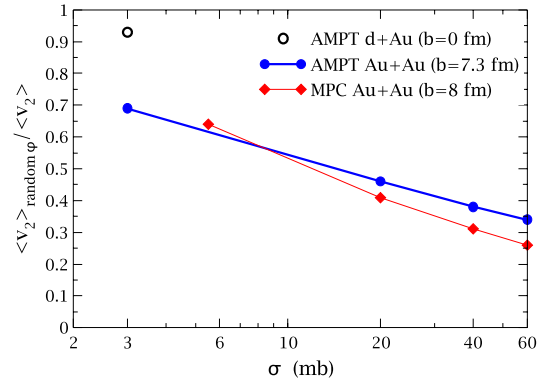


Fig. 5. Parton v_2 ratios as functions of the parton cross section for d+Au and Au+Au collisions.

Therefore we have changed σ in the AMPT model arbitrarily up to 60 mb [7] with the results shown in Fig.4 (curves with circles). MPC results are also shown (curves with diamonds), where $\langle v_2 \rangle$ values are bigger partly due to the usage of an isotropic $d\sigma/dt$. Note that $d\sigma/dt$ in AMPT has a Debye-screened form [2]. We see in Fig.4 that $\langle v_2 \rangle$ from the normal transport results increases or roughly saturates when the cross section increases, while $\langle v_2 \rangle$ from the azimuth-randomized tests decreases with the cross section.

Fig.5 shows the ratio of the azimuth-randomized $\langle v_2 \rangle$ over the normal $\langle v_2 \rangle$, which can be considered as an estimate of the fraction of $\langle v_2 \rangle$ from the escape mechanism. As expected, this ratio from either AMPT or MPC decreases with σ (roughly linear with $\ln \sigma$), verifying our expectation that $\langle v_2 \rangle$ is eventually dominated by hydrodynamic-type flow at very high cross sections. However, at $\sigma = 3$ mb which enables the AMPT model to reasonably reproduce the bulk data [11], $\langle v_2 \rangle$ is dominated by the escape mechanism.

3. Summary

Using two different transport models, we find that the majority of v_2 comes from the anisotropic escape of partons, not from the parton collective flow, even for semi-central Au+Au collisions at 200A GeV. This is more true for smaller systems such as central d+Au collisions. The domination of v_2 by the escape mechanism corresponds to low and modest $\langle N_{\text{coll}} \rangle$, the average number of scatterings each parton suffers. At very large $\langle N_{\text{coll}} \rangle$ (or at unrealistically large parton cross sections), on the other hand, we find that hydrodynamic-type collective flow will eventually dominate. So the key question is which case heavy ion collisions in RHIC and LHC energies belong to, and further studies are needed in order to identify unique signatures of the escape mechanism. If confirmed, our finding could change the paradigm of anisotropic flow. In addition, we find that the escape mechanism still contributes $\sim 30\%$ of the final parton $\langle v_2 \rangle$ even at the parton cross section of 60 mb. Since parton escape is inevitable for transient collision systems, it is also important to examine the possible role of the escape mechanism in the hydrodynamics framework.

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